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THE FLUIDIZATION PATTERN OF DENSITY-SEGREGATING TWO-SOLID BEDS

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ABSTRACT

An experimental work is presented meant to clarify the specific role played by density differences between components in the segregating fluidization process of two-solid beds. The overall behaviour of such systems is characterized by substituting the traditional concept of “minimum fluidization velocity” of the binary mixture with the “velocity interval of fluidization” of the bed, which is limited by its “initial” and “final” fluidization velocity”.

The dependence of these characteristic velocities on parameters such as component densities and mixture composition is illustrated by several series of experiments. The experimental results are analysed in the light of the fundamental theory, so as to establish quantitative relationships for their prediction. The evolution of the axial profile of component concentration at varying fluidization velocity is also discussed.

INTRODUCTION

A well-known feature of fluidized beds of different materials is the tendency of their particulate components to form stratified layers in response to the dragging action of the upflowing gas. Segregation is mainly driven by density or size differences among the particles that constitute the bed, two factors which act simultaneously when a charge of fully dissimilar solids is processed. Even with mixtures of only two solids predicting the equilibrium distribution of their components along the column height from the knowledge of particle properties, bed composition and fluidization velocity still constitutes a goal of the research in the field. To overcome these difficulties, a necessary step seems that of improving our present understanding of the fluidization process of two-component beds as well as that of the mutual dependence between fluidization and segregation of bed components.

Because of the large number of variables involved in the phenomenology of segregating fluidization, a traditional method of investigation is that of dealing with binary systems in which only one of the two segregation factors, inequality of component density or size, is present. However, in comparison with the number of studies devoted to size segregating mixtures, much fewer are those focused on the fluidization properties of two-density beds and the specific influence of density differences on segregation. Besides the relative lack of information on this topic, an added difficulty is that connected with the impossibility of characterizing the behaviour of binary fluidized beds with reference to their minimum fluidization velocity, a parameter shown to be devoid of any significance out of the field of monosolid fluidization (1).

Therefore, on developing the approach first proposed by Chen and Keairns (2) and followed so far by a minority of authors (3-6), this paper looks at the actual nature of fluidization of two-density particle systems as that of a gradual process that has place along a whole velocity interval rather than at the critical velocity threshold u_{mf} typical of monodensity beds.

On the pressure drop versus gas velocity diagram like that of Fig.1 the two boundaries of the velocity interval of fluidization are clearly identified: the *"initial fluidization velocity"* u_{if} is that at which Δp first deviates from the fixed bed line, while the *"final fluidization velocity"* u_{ff} is located where the ultimate value of Δp, equal to the total bed weight per unit section, is first attained.

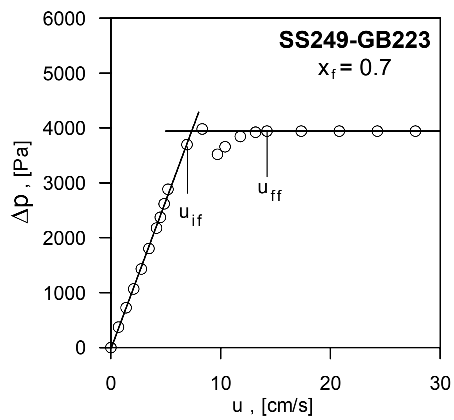

Fig.1 - Fluidization diagram of a two-density mixture.

Based on their respective definitions, these characteristic velocities are strictly dependent on the nature and the extension of the transient along which the whole bed is gradually brought, from top to bottom, into the suspended state. As a consequence, not only is the amplitude of the fluidization velocity interval, given by the difference $u_{ff} - u_{if}$, a function of the specific mixture considered and of its average composition but it also depends on the distribution of its components in the packed bed (1).

EXPERIMENTAL MATERIALS, EQUIPMENT AND TECHNIQUE

The present study was aimed to investigated the fluidization behaviour of binary beds constituted by spherical solids of nearly equal average diameter. The materials employed, together with their essential properties, are reported in Table 1. All solids were closely sieved so as to minimize their granulometric spread; their densities were measured by a helium pycnometer.

Table 1. Properties of mixture components.

PARTICLES	ρ [g/cm^3]	**d** [μm]	u_{mf} [cm/s]
Molecular sieves (MS)	1.46	624	20.8
Glass ballotini (GB)	2.48	223 / 428 / 593 / 661	4.3 / 17.9 / 30.3 / 30.8
Ceramic (CE)	3.60	701	43.3
Steel shots (SS)	7.70	249 / 439	17.3 / 43.3

The experimental campaign reported in this paper was performed on four mixtures, whose composition was made vary by adjusting the amount of the two components in a way that the packed bed could maintain a fixed aspect ratio H_b/D, constantly equal to 1.7. The binary beds investigated are listed in Table 2, where the size and density ratio between their "jetsam" and "flotsam" components, as defined by Rowe et al. (6), is also reported.

Table 2. Size and density ratio of the mixtures.

MIXTURE (jetsam / flotsam)	d_j / d_f	ρ_j / ρ_f	**m** (parameter of eqn 3)
CE701-GB661	1.06	1.45	6
GB593-MS624	0.95	1.70	3
SS249-GB223	1.12	3.10	6
SS439-GB428	1.03	3.10	14

Experiments were carried out in a perspex column of 10 cm ID, equipped with a plastic porous gas distributor. The fluidizing gas was air, whose flow rate was regulated by a set of rotameters. Pressure drops across the whole particle bed were measured by a water manometer connected to a tap located 1 mm above the distributor plane.

The axial profile of component concentration was determined by applying the so-called "freezing procedure", i.e. by instantaneously cutting the fluidizing gas feed off by means to a solenoid valve. A vacuum device was used for drawing the solids from the top of the column in horizontal layers 2 cm thick. After separating and weighing the components of each sample, the volume fraction of either species was evaluated and referred to the average height of the relevant layer. This procedure allowed reconstructing the axial concentration profile of the flotsam component (namely the curve of x_f versus H) at the fluidization velocity of interest.

RESULTS AND DISCUSSION

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The strength of the segregation tendency acting in a two-density mixture subjected to fluidization is easily observed to grow with the increase of the component density ratio ρ_j/ρ_f. When this ratio is rather close to unity, the process of fluidization by which a well-mixed packed bed achieves the fluidized state results in a nearly homogeneous bed; on the other hand, mixtures having higher density ratios quickly give place to the formation of stratified layers of either solid.

Although concealed under this substantial dissimilarity, the common features of the fluidization behaviour of two-density mixtures can be recognized by analysing the dependence of their velocity interval of fluidization on bed composition. In the present work this has been done by performing series of experiments in which the composition of each mixture was made change while keeping the bed aspect ratio H_b/D fixed at a value of about 1.7. From each of these tests a diagram similar to that of Fig.1 was obtained, capable to provide the relevant values of u_{if} and u_{ff}.

The fluidization velocity diagram of density segregating binary mixtures

As summarized in Table 2, the jetsam/flotsam component density ratio of the mixtures examined in this study varies from 1.45 to 3.10, a range sufficiently wide to cover many situations of practical interest. The experimental dependence of the two boundaries of their velocity field of fluidization on the volumetric fraction of the flotsam component is reported in Figs 2 and 3.

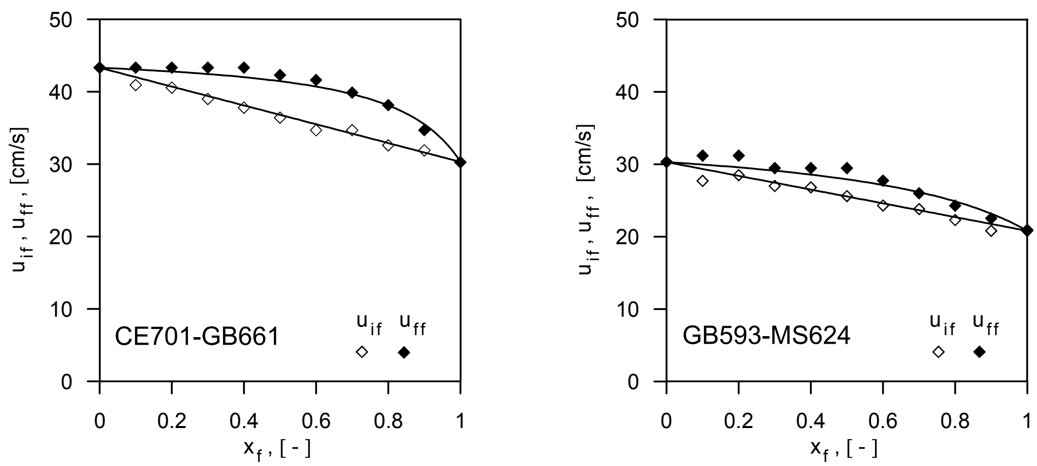

Fig.2 - The fluidization velocity interval of mixtures of low component density ratio.
CE701-GB661: ρ_j/ρ_f=1.45 ; GB593-MS624: ρ_j/ρ_f=1.70

The former couple of diagrams is meant to illustrate the trends of u_{if} and u_{ff} of systems whose component density ratio is relatively low while the latter represents the opposite case; at the same time mixtures SS249-GB223 and SS439-GB428 allow comparing the properties of beds of equal density ratio but different particle diameter.

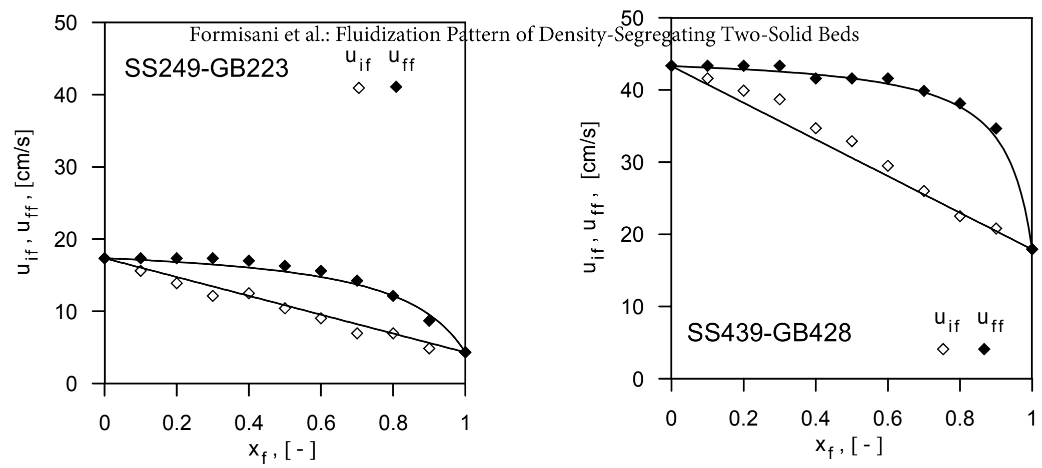

Fig.3 - The fluidization velocity interval of mixtures of high component density ratio. SS249-GB223 and SS439-GB428: ρ_j/ρ_f=3.10

Notwithstanding what will turn up to be a visible difference of behaviour in their segregation pattern, both types of systems exhibit a unique fluidization behaviour. With no exception, the shape of the fluidization diagram of all binary beds is that of a curvilinear triangle. Whatever the density ratio between mixture components, the locus of the initial fluidization velocity of the mixture is the straight line that joins the minimum fluidization velocities of the two components of the binary bed, located at the extremes of the composition field.

It can therefore be stated that for a well-mixed binary bed u_{if} is the weighed average of the minimum fluidization velocities of its components:

$$u_{if} = x_f u_{mf,f} + \left(1 - x_f\right) u_{mf,j} \tag{1}$$

When dealing with mixtures of spherical particles of the same size, both solids, on their own, exhibit nearly the same incipient fluidization voidage ε_{mf}. Furthermore, it can reasonably be assumed that such a unique value of the minimum fluidization voidage is insensitive to the relative amount of the two species, so as to rest unvaried at all values of x_f. As far as these approximations hold, eqn (1) gives place to a modified form of Carman-Kozeny equation:

$$180 \frac{\mu_g u_{if}}{d^2} \frac{\left(1-\varepsilon_{mf}\right)^2}{\varepsilon_{mf}^3} = \left[\left(\rho_f - \rho_g\right) x_f + \left(\rho_j - \rho_g\right)\left(1 - x_f\right)\right] g \left(1 - \varepsilon_{mf}\right) \tag{2}$$

As for the experimental dependence of the final fluidization velocity on x_f, it is represented, for all mixtures, by an increasingly sloping curve. For any binary bed, therefore, the progressive reduction of the volumetric fraction of its jetsam (denser) component makes the velocity at which system suspension is completed increasingly lower than $u_{mf,j}$. The relation between final fluidization velocity and mixture composition is well represented by the empirical equation

$$\frac{u_{ff} - u_{mf,f}}{u_{mf,j} - u_{mf,f}} = \frac{m\left(1 - x_f\right)}{m\left(1 - x_f\right) + x_f} \quad , \tag{3}$$

whose only parameter m can be determined by a single measure of u_{ff} at a know value of x_f.

In Figs 2 and 3 curves of u_{if} and u_{ff} derived from eqns (2) and (3), respectively, are compared with the experimental data of the two characteristic velocities of each mixture. Values of the parameter m relevant to each mixture are reported in Table 2. The physical meaning of this parameter is not yet quite clear, but its values are apparently related to the difference between the minimum fluidization velocities of mixture components (namely $u_{mf,j} - u_{mf,f}$). That implies that the component density ratio is not the only factor which determines the fluidization and segregation pattern of beds of two solids of the same size, as their behaviour is also affected by the absolute value of their particle diameter.

An overall picture of the ability of eqn (3) to represent the dependence of the upper limit of the fluidization velocity interval on the constitutive variables of the binary bed is given in Fig.4, where the comparison with the complex of u_{ff} data shows that errors are limited to ±10%.

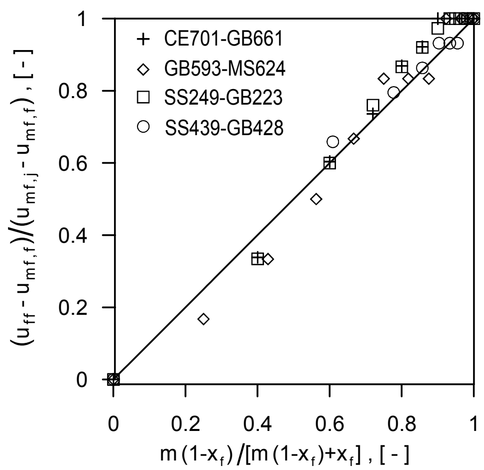

Fig.4 - Comparison between experimental data of u_{ff} and predictions of eqn (4).

Segregation and remixing of mixture components during the fluidization process

Binary mixtures whose packed arrangement is that of a homogeneously mixed bed begin to undergo component stratification as soon as the gas velocity equals the value of their u_{if}, this being the limit under which all particles are immobile.
By gradually rising u over the initial fluidization velocity level, the axial concentration profile continuously changes, through a succession of equilibrium states that bring the bed first to a state of maximum segregation and then to one of partial or total remixing.

Such phenomenon is illustrated in Fig.5 where possible differences of behaviour induced by a low or a high density ratio of mixture components are analysed by comparing the results relevant to CE701-GB661 and SS439-GB428.

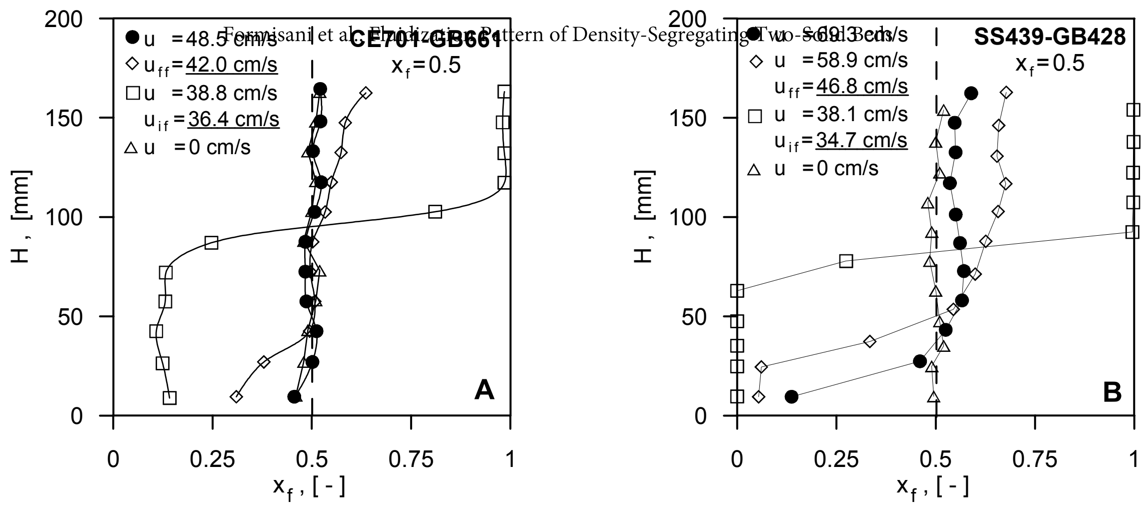

Fig.5 - Axial concentration profiles of the flotsam component at varying fluidization velocity. A) CE701-GB661: ρ_j/ρ_f=1.45 ; B) SS439-GB428: ρ_j/ρ_f=3.10

Leaving from the flat axial profile of the packed bed, each of the two systems shows a state of strong stratification at a velocity level intermediate to the limits of its fluidization velocity interval. At this stage the only clear difference between systems characterized by a strong difference in their component density ratio is that segregation is never complete for a mixture like CE701-GB661, for which some residual amount of jetsam is found in the top flotsam-rich layer of the bed. Much more significant is the presence of the flotsam species in the bottom region of the column.
Consistent with the stronger tendency to segregation of a system like SS439-GB428 is the fact that velocities much higher than its u_{ff} are required for bringing the mixture back to a state in which the two solids are nearly perfectly mixed, with a deviation from the theoretical value of 0.5 which has been shown to be related to the peculiar fluid dynamics prevailing in the grid region (7). As regards instead CE701-GB661, the velocity at which the homogeneity of the bed is restored results closer to u_{ff} and the axial profile of x_f nearly coincides with average mixture composition.

Further to throwing some light on the influence exerted by the parameter ρ_j/ρ_f on the extent of segregation phenomena, these results indicate that, similar to the case of the initial and final fluidization velocities, the operating velocity at which a two-density bed can re-achieve the fully mixed condition has to be a function of the properties of its components as well as of mixture composition. Definition of this dependence, left to future work, constitutes an objective of great interest as it would help devising criteria of regulation and control of the mixing state of multisolid fluidized bed processes.

CONCLUSIONS

1. Far from being a stepwise process occurring at a given u_{mf}, fluidization of a binary mixture of solids of equal size but differing in density is a gradual process that has place along a whole velocity interval limited by the initial and final fluidization velocities of the particle system.
2. Irrespective of the density ratio of its components, the fluidization velocity interval of any two-density mixture exhibits the same type of dependence on

composition.

3. When the two components are uniformly distributed in the packed bed, the boundaries of this interval, u_{if} and u_{ff}, can be calculated by relationships that relate each of the two parameters to the constitutive properties of mixture components and bed composition.
4. The component density ratio of the mixture is a variable that affects the segregation pattern of the binary bed, as it determines the extent of stratification and the velocity at which the two solids are brought back to the fully mixed state.

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NOTATION

d	particle diameter, μm
D	bed diameter, mm
H	height, mm
H_b	bed height, mm
g	gravity acceleration, cm/s^2
m	parameter in eqn (3), -
Δp	pressure drop, Pa
u	superficial gas velocity, cm/s
u_{mf}	minimum fluidization velocity, cm/s
x_f	volumetric fraction of flotsam, -
ε_{mf}	minimum fluidization voidage, -
μ_g	gas viscosity, g/(cm s)
ρ	solid density, g/cm^3
ρ_g	gas density, g/cm^3

Subscripts

f, j	the flotsam, jetsam component
if, ff	at initial, final fluidization

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